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**Carbon and Environmental Footprinting of
Low Carbon UK Electricity Futures to 2050**

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ABSTRACT

Electricity generation contributes a large proportion of the total greenhouse gas emissions in the United Kingdom (UK), due to the predominant use of fossil fuel (coal and natural gas) combustion for this purpose. A range of future UK energy scenarios has been employed to determine their resulting environmental and carbon footprints. The three scenarios were characterised as ‘Business As Usual’ (BAU), ‘Low Carbon’ (LC) and ‘Deep Green’ (DG) futures, and yielded possible electricity demands out to 2050. It was found that the environmental footprint of the current power network is 41 million (M) *global hectares* (gha). If future trends follow a BAU scenario, then this footprint is observed to fall to about 25 Mgha in 2050. The LC scenario implies an extensive penetration of micro-generators in the home to satisfy heat and power demands. However, these energy requirements are minimised by way of improved insulation of the building fabric and other demand reduction measures. In contrast, the DG scenario presupposes a network where centralised, large-scale renewable energy technologies (mainly wind turbines) have an important role in the power generation. However, both the LC and DG scenarios were found to lead to footprints of less than 4 Mgha by 2050.

KEYWORDS: Carbon footprints; Environmental footprints; Electricity futures; Energy systems analysis; Sustainability; United Kingdom

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1. INTRODUCTION

1.1 Background

Electricity generation presently contributes approximately 30% of United Kingdom (UK) carbon dioxide (CO₂) emissions [1], the principal ‘greenhouse gas’ (GHG) having an atmospheric residence time of about 100 years [2]. This is predominantly due to the use of fossil fuel (coal and natural gas) combustion for this purpose. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to quite dramatic increases since 1950 in the ‘basket’ of GHGs incorporated in the Kyoto Protocol; concentrations rising from 330 ppm to about 430 ppm currently [3]. Prior to the first industrial revolution the atmospheric concentration of ‘Kyoto gases’ was only some 270 ppm. The cause of the observed rise in global average near-surface temperatures over the second half of the 20th Century has been a matter of dispute and controversy. But the most recent (2007) scientific assessment by the Intergovernmental Panel on Climate Change (IPCC) states with ‘very high confidence’ that humans are having a significant impact on the global warming [3]. They argue that GHG emissions from human activities trap long-wave thermal radiation from the Earth’s surface in the atmosphere (not strictly ‘greenhouse’ phenomena), and that these are the main cause of rises in climatic temperatures. In order to mitigate anthropogenic climate change, the *Royal Commission on Environmental Pollution* in the UK [4] recommended at the turn of the Millennium a 60% cut in UK CO₂ emissions by 2050. The British Government subsequently set a tougher, legally binding target of reducing the nation’s CO₂ emissions overall by 80% by 2050 in comparison to a 1990 baseline [5].

The history of electricity generation since the time of Edison has been based around the concept of employing large, centralised power stations (see, for example, Buchanan [6], Hammond [2] and Hughes [7]). Thus, the bulk of electricity in Britain is still generated by large thermal power plants that are connected to a high-voltage transmission grid, and is then distributed to end-users via regional low-voltage distribution networks [1,8]. The whole UK energy system is represented schematically in Fig.1 [2], where the electricity network is clearly illustrated. This centralised model has delivered economies of scale and reliability [9], but there are significant drawbacks. It suffers, for example, from overall energy system losses of about 65% in terms of primary energy input [2,9-11]. These losses predominantly result from heat wasted during electricity production (58%), but there are smaller losses rising in transmission and distribution - approximately 1.5% and 5% respectively [1,9]. The use of micro-generation and other decentralised or distributed power technologies has the potential to reduce such losses. It has recently been predicted that micro-generation could provide 30–40% of the country’s electricity needs by 2050 [9].

1.2 The Issues Considered

Environmental or ‘ecological’ footprints (*ef*) have been widely used in recent years as indicators of resource consumption and waste absorption transformed on the basis of biologically productive land area [in global hectares (gha)] required *per capita* with prevailing technology [12-16]. They represent a partial measure of the extent to which an activity [that might be associated with communities, technologies, or systems] is ‘sustainable’ [14,15]. In contrast, ‘carbon footprints’ (*cf*) are the amount of carbon [or carbon dioxide equivalent (CO_{2e})] emissions associated with such activities [17,18], and are closely related to environmental footprints. But, unlike the latter, they are generally presented in terms of units of mass or weight (kilograms per functional unit), rather than in spatial units (such as gha).

These carbon footprints have become the ‘currency’ of debate in a climate-constrained world [18]. They are increasingly popular ecological indicators, adopted by individuals, businesses, governments, and the media alike. Carbon and environmental footprint analysis have been employed in the present study to estimate the environmental impacts associated with UK power generation based on historic data and alternative energy scenarios out to 2050. Thus, the UK *Electricity Supply Industry* (ESI) is evaluated on a ‘whole systems’ basis, within an overall ‘sustainability framework’ [2,14,15]. The current footprint analysis is consistent with that developed by the *Global Footprint Network* and related bodies. The environmental footprint (*ef*) was broken down respectively into carbon (effectively *cf*), embodied energy, transport, built land, water, and waste components. *ef* was then determined on an annual basis from 1950-2050. Uncertainties related to both footprints were estimated using an established procedure for uncertainty analysis [15,19].

Historical electricity consumption data was available from UK national statistics for different fuel types over the period from 1950 [9]. In order to determine future trends in the power sector footprints, a range of future energy scenarios were adopted that had previously been developed for the UK SUPERGEN Research Consortium on ‘*Highly Distributed Power Systems*’ (HDPS) by Jardine and Ault [20]: funded under the auspices of the UK *Research Councils’ Energy Programme*. The original aim of these scenarios was to study the potential for extensive penetration of micro-generators into the British electricity network. They were developed from a synthesis of those that had been earlier devised for future network technologies on the one hand, and domestic energy demands on the other. Three resulting scenarios were characterised as ‘Business As Usual’ (BAU), ‘Low Carbon’ (LC) and ‘Deep Green’ (DG) futures, and yielded possible future electricity demands to 2050. The present contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems [2,8,9,11] in the broad context of transition pathways towards a low carbon future for the UK [21].

2. THE UK ELECTRICITY SYSTEM

The UK ESI currently has a heavy reliance on primary fuels, particularly coal and natural gas. Cheap coal from overseas is unlikely to cause a security of supply problem, but the increasing reliance being placed on imports of natural gas for *Combined Cycle Gas Turbine* (CCGT) power plants brings with it potential risks. Britain became a net importer of natural gas in 2004 as reserves in the UK continental shelf declined [8,10,22]. In the long-term there is considerable uncertainty about the security of imported gas supplies. The largest natural gas reserves globally are found in Russia, North Africa, and the Middle East. Even without the obvious political problems associated with these regions, there will be difficulties in terms of the transportation of gas from these areas. Long pipelines, additional port and storage capacity will all be required. The natural gas interconnector between Norfolk (in the East Anglian region of England) and Belgium means that gas can flow out of Britain to the continental market, as well as inward to meet domestic demand. In 2010 the UK produced 665,083 GWh of indigenous natural gas, with its net imports amounting to some 413,098 GWh [9]. Imports are likely to continue to grow quite rapidly in the near future.

The UK electricity system is made up of companies performing different functions: the generators, network companies, and suppliers [8,22]. *National Grid* (NG) acts as the system operator with responsibility for balancing power supply and demand. The ‘generators’ own and operate large power stations: coal-fired stations, CCGT plant, nuclear power stations, wind farms, and various smaller contributors. Thirty large (>1GW_e) power plants meet the

bulk of electricity demand [7]. This is typically $\sim 40\text{GW}_e$, although it rises to $\sim 60\text{GW}_e$ at peak. NG is also the ‘Transmission Network Owner’ (TNO) for England and Wales, whilst *Scottish Power* and *Scottish and Southern* are the TNOs in Scotland. The ‘grid’ is made up of $\sim 25,000$ km of high voltage overhead lines (275kV or above) that minimise energy losses over distance. There are currently some fourteen regional distribution networks in Great Britain with 800,000 km of overhead lines and underground cables [7]. They deliver lower voltage (132kV and below) power from grid supply points to consumers. These regional networks are managed, in turn, by seven companies that act as *Distribution Network Operators* (DNOs). Much of the grid was constructed in the 1950s and 1960s. It is therefore heavily reinforced in former coal-mining areas, and is nearing the end of its design life [8,22]. There are ‘bottlenecks’ restricting power flow from Scotland to England (2.2GW_e), and via the interconnectors (in the form of high-voltage undersea cables) to France and Northern Ireland. The grid will require both renewal and reconfiguration in order to accommodate distributed generation.

3. UK ENERGY FUTURES

3.1 The Parent Scenarios

The scenarios employed for the present study were created by Jardine and Ault [20] as a synthesis of the earlier SUPERGEN *Future Network Technologies* (FNT) scenarios of Elder *et al.* [23] and the *UK Domestic Carbon Model* (UKDCM2) produced by Layberry [24]. The FNT scenarios [23] were supply-side focused and described six high-level UK electricity networks as they might appear in 2050. Each considered various technical, economic, environmental and regulatory constraints on the UK ESI. They yield different penetrations of centralised generators (including large-scale renewables) and capacity mixes, as well as network infrastructures. In contrast, the UKDCM2 model [24] takes a demand-side approach, with energy use and carbon dioxide emissions from the UK housing stock being determined from inputs on household numbers, house type, thermal efficiency, and appliance efficiency, together with the number and efficiency of micro-generators used. It was employed to estimate electricity demand for households based on the assumed stock of lights and appliances, as well as building type (insulation levels, internal temperatures, and occupancy). The total electricity demand was then determined from the sum of this and non-domestic power demand split between industrial and other uses.

3.2 The SUPERGEN *Highly Distributed Power Systems* (HDPS) Scenarios

The HDPS scenarios [20] were developed from a synthesis of those that had been devised earlier (and outlined above) for future network technologies on the one hand, and domestic energy demands on the other. Jardine and Ault [20] created a set of three normative scenarios in order to examine the specific consequences of extensive penetrations of micro-generators into British electricity networks. The integration of the two sets of predecessor scenarios [20] kept the level of details of each parent approach, while allowing for key parameters that influence electricity networks. They have provided a useful tool for unifying contributions across HDPS project partners [25], quantifying the scale of the change required (moving from a centralised system to one where perhaps 1/3 of electricity comes from distributed sources), and to ensure that the suggested futures were in line with the UK Government’s initial target of a 60% reduction in CO_2 by 2050. This level of distributed power presents significant challenges, including reverse power flow on networks, load balancing, storage requirements, phase unbalance, harmonics, and ancillary services [25]. The resulting three scenarios were characterised as ‘Business As Usual’ (BAU), ‘Low Carbon’ (LC) and ‘Deep Green’ (DG) futures, and yielded possible electricity demands to 2050. The BAU scenario [20] is based on

incremental change over time with a continuation of near-term trends in technologies, as well as energy policy responses to the climate change and energy security challenges. Growth in the take-up of decentralised energy resources (DERs) is assumed to be consumer-led, rather than stimulated by an act of government policy intervention. In contrast, the LC scenario [20] implies an extensive penetration of micro-generators in the home to satisfy heat and power demands. However, these are minimised by way of improved insulation of the building fabric and other demand reduction measures. Under this scenario, DERs contributes ~44% of UK electricity supply by 2050, and residential dwellings are significant net exporter of power. Finally, the DG scenario [20] presupposes a network where centralised renewable energy technologies – mainly large-scale onshore and offshore wind turbines - have a significant role in power generation. Demand reduction again plays an important role (in a similar manner to that with the LC scenario), but fossil fuel power generation is effectively eliminated. The scenarios do not take account any increase in electricity demand associated with the possibility of much greater use of electric heat pumps for home heating or electric vehicles for transport. This is justified on the basis of a ‘like-for-like’ comparison.

4. CARBON AND ENVIRONMENTAL FOOTPRINTING

4.1 The Ecological or Environmental Footprint Methodology

The use of ‘ecological’ or environmental footprint analysis has grown in popularity over recent years, both in Europe and North America. They provide a simple, but often graphic, measure of the environmental impact of human activity: whether or not, in the foreseeable future, humanity will be able to “tread softly on the Earth” [2]. William Rees used footprint analysis in its basic form to teach planning students for some 20 years (see Wackernagel and Rees [12]). He decided to adopt the term ‘ecological footprint’ in the early 1990s, rather than ‘appropriated carrying capacity’ that he had previously used, after buying a new television set [13]. It had a smaller footprint (that is, took up less space) than his old model. The terms ‘environmental’ and ‘ecological’ footprints are used interchangeably here (as they were previously by Hammond [14] and Eaton *et al.* [15]), although the former expression is preferred. Ecology is that branch of biology dealing with the introduction of organisms and their surroundings. ‘Human ecology’, sometimes used for the study of humans and their environment, is closer to the usage implied by footprint analysis.

Footprint calculations involve several steps. Initially the land area per functional unit (e.g., *per capita* or, in the present case, per GWh) appropriated for each major category of consumption (aa_i) is determined:

$$aa_i = \frac{c_i}{p_i} \sim \frac{\text{annual consumption of an item}}{\text{average annual yield}}$$

In the original version of environmental footprint analysis (EFA) employed by Wackernagel and Rees [12], four consumption categories were identified: energy use, the built environment (the land area covered by a settlement and its connection infrastructure), food, and forestry products. This is a restricted subset of all goods and services consumed, which was determined by the practical requirements of data gathering and influenced by the development of the technique in a Canadian setting. Five land types are typically been employed: Chambers *et al.* [13], for example, adopted bioproductive land, bioproductive sea, energy land, built land, and the land needed to secure biodiversity as their categories (see also Eaton *et al.* [15] and Fig. 2). Here the components analysed, in addition to the carbon footprint,

were ‘built land’, ‘embodied energy’, ‘materials and wastes’, ‘transport’, and ‘water’. In order to calculate the footprint per functional unit (ef) in global hectares (gha), the appropriated land area for each consumption category is then summed to yield:

$$ef = \sum_{i=1}^{i=n} aa_i$$

One global hectare represents a hectare (ha) of biologically productive land at the average global productivity. Different footprint components need to be standardised, so that global hectares account for disparities in land productivities. This computation then leads to a matrix of consumption categories and land use requirements, which is ideally suited to a spreadsheet implementation. In order to determine the total footprint for a given country, region or community (EF), the functional unit value (ef) is simply multiplied by the relevant population size (N), viz.

$$EF = ef(N)$$

4.2 The Carbon Footprint Component

The concept of the ‘carbon footprint’ (cf) is rooted within the framework used to determine the eco-footprint. However, Hammond [17] noted that a ‘footprint’ would normally be measured in spatial units [such as global hectares (gha)], whereas the carbon footprint is typically presented in mass (or weight) units, i.e., kilograms or tonnes. He therefore argued that it should perhaps be termed a ‘carbon weight’ (C_w) or something similar. Wiedmann and Minx [26] reviewed various suggestions, including that of Hammond [17], and then proposed a definition for the ‘carbon footprint’ as including the “total amount of CO₂ emissions that is directly and indirectly caused by an activity”. Unfortunately, no definition has been formally adopted in a standard with the agreement of the communities involved. Indeed, many organisations have adopted the use of the term carbon footprint when assessing the carbon dioxide emissions released during various processes or activities, although these are again measured in tonnes of carbon dioxide [18].

4.3 Other Components of the Environmental Footprint

The initial phase of footprint analysis involves the collection of consumption data covering the various components. This yields the flow of resources into and out of the UK electricity sector. Proxy (or secondary) data adapted from national statistics was employed in the absence of sector-specific obtained (or primary) data. This collation and analysis of data is highly disaggregated with very many individual items of information. In addition to the consumption data needed for footprint analysis, yield and conversion (or ‘equivalence’) factors were required. The EFA resource components had to be identified and categorised (see Fig. 3). They reflected broad and identifiable policy making categories, which match the consumption of ‘natural capital’ [15,27]. In the present study, these components (see also the ‘block diagram’ in Fig. 4) were:

- Built Land: Land appropriated for power sector development.
- Embodied Energy: The quantity of energy required for the construction of power plants or to process fuels for the sector [28].
- Materials and Waste: Consumption of products and materials for use within the power sector.
- Transport: ‘Full fuel cycle’ transportation requirements.
- Water: The use of water within the power sector.

‘Double accounting’ can arise when the embodied energy component [28] includes the energy used in production; fuels for electricity generation here. Thus, in the present study, the embodied energy incorporates only the ‘upstream’ use of energy, whilst the carbon footprint represents the direct fuel inputs for power production (e.g., fossil fuels for boiler combustion).

4.4 Uncertainty Analysis

The uncertainties in EFA are dependent on the accuracy of the data collected. Some of the data represents a proxy adopted from national resource consumption statistics, and hence errors are inevitably present in footprint calculations. Footprint uncertainties were calculated using a ‘standard’ method developed originally by Kline and McClintock [19] for single-sample experiments in engineering research; see the Appendix below. Here estimates of uncertainties were based on a careful assessment of errors in the various primary and secondary (or proxy) sources (see also Eaton *et al.* [15]).

5. ANALYSIS OF UK ELECTRICITY FUTURES TO 2050

5.1 UK Electricity Supply and Demand: Historic Data

The annual electricity consumption by fuel type in the UK since 1950 was obtained from the annual *Digest of UK Energy Statistics* (DUKES) [9]. Coal has played an important role in electricity generation over the past half century, and still accounts for approximately a third of the electricity consumed today [2,9]. Oil-fired power plants were introduced in the late 1950s and their use fluctuated throughout from the 1960s to the 1980s, before falling in the 1990s to less than 4% today [8,10]. Natural gas is responsible for about a further third of electricity produced at the present time, following the so-called ‘dash for gas’ after energy market liberalisation in the early 1990s [2,8]. Nuclear power generation accounts for around 20% of UK electricity supply [7-9], which grew steadily following its introduction in the late 1950s until the early 1990s. Thereafter it has been in slow decline, due to decommissioning of the earliest nuclear power plant designs (the Magnox and Advanced Gas-cooled Reactors). A small contribution has been made from large-scale hydropower schemes since the late 1950s. The construction of onshore, and recently offshore, wind turbine arrays has made a modest contribution since the 1990s [2,9], and the biomass co-firing of coal-fired power plants (in order to offset carbon emissions) was introduced in the 2000s.

The environmental footprints per unit electricity (*ef*) associated with power generators in the ‘baseline’ year (taken as 2005) are depicted in Fig. 5. Here the functional unit employed is the GWh, and thus the footprints are presented in terms of gha/GWh. Carbon emissions or footprints are largely associated with fossil-fuelled power plants. The environmental footprints of these plants were coal - 158 gha/GWh, oil - 122 gha/GWh, and natural gas - 80 gha/GWh. Nuclear power and renewables (other than bioenergy) are near zero carbon emitters. Their *ef* values are consequently 57 gha/GWh and <25 gha/GWh respectively. Solid (so-called ‘first generation’) biofuels give rise to potentially significant emissions, and exhibit the highest land-take of any of the technologies shown in Fig. 5. They therefore lead to the largest *ef* value of 214 gha/GWh. The plants categorised as ‘Other’ represent other thermal sources that include those from various coke oven gas, blast furnace gas, waste products from chemical processes, and refuse derived fuels. It gives rise to the second largest footprint per unit electricity at 194 gha/GWh. Nevertheless, the overall environmental footprint (EF) of such plants is relatively insignificant, because their total power capacity is small.

5.2 The 'Business as Usual' (BAU) Scenario

The projected electricity consumption by fuel type according to the BAU scenario is illustrated in Fig. 6 below. It can be seen that total demand is expected to gradually rise to around 430 TWh per year by 2025 and thereafter it remains fairly stable. There will be a gradual decline in electricity generated from coal-fired power plants to less than 50 TWh per year over the next 30 years, which will initially be balanced by a rapid increase in natural gas. It is anticipated that CCGT plants with carbon capture and storage (CCS) facilities will be introduced around 2020 [29]. This will gradually replace conventional gas-fired power station, with CCGT/CCS schemes reaching a total output of 98 TWh by 2050 compared to 130 TWh from conventional gas. Oil and other thermal fuels will be slowly phased out, and nuclear power will decline to approximately 33 TWh per year by way of “replacing nuclear by nuclear”, i.e., replacing decommissioned nuclear power plants by ‘new build’ nuclear power reactors. Much of the initial increase in demand is likely to be met by onshore and offshore wind power, which is projected to continue to grow and replace conventional generators up to about 100 TWh in 2050. Finally, marine technologies (tidal barrages, tidal stream and wave power devices) are assumed to be introduced around the mid-2020s, and slowly become established to produce around a modest 20 TWh by 2050.

The BAU scenario suggests, as depicted in Fig. 7, a gradual decline of the environmental footprint per GWh of electricity produced (*ef*) over the period from the present day until 2050. This is similar to the historical decline during 1950-2000, and it should therefore be possible to achieve the projected footprint of 67 gha/GWh in 2050. The corresponding total environmental footprint (EF) from 1950 to 2006 calculated from published historical data [9] was found to grow rapidly from 10 million (M) *global hectares* (gha) in 1950 to over 35 Mgha per year by the late 1970s, due to the increase in electricity use [2]. The latter figure is about twice the physical area of agricultural land in the UK. There was a notable drop in the footprint in early 1980s, which coincides with a drop in coal generation caused by the national coal miner's strike of 1983/84. Throughout the 1990s the environmental footprint has fluctuated between 35-40 Mgha, due to the introduction of gas-fired power stations – the ‘dash for gas’ - and new nuclear power plant (such as the Sizewell B plant in Suffolk). These have a lower impact on the environment per GWh of electricity produced than conventional coal-fired power stations. The BAU scenario indicates that the total environmental footprint (EF) out to 2050 will remain high until about 2020 contributions (see Fig.8), when it will start to decline slowly before stabilising at around 28 Mgha per year in 2040. This is because, although the reduction in coal use will continue and be replaced by lower carbon technologies, the demand for electricity will continue to grow until around 2025 as depicted in Fig. 6. It was found that historically just over a half of the total environmental footprint (EF) was as a result of the carbon footprint (weight) of the UK power sector, and that a further 40% resulted from the embodied energy and transport, while built land, water and waste make fairly insignificant contributions (see again Fig.8). The BAU scenario suggests that initially the proportion of the footprint resulting from carbon emissions will increase, but once electricity demand stabilises in the mid-2020s, this proportion will decline as a result of the increasing capacity of low carbon technologies. Although the annual environmental footprint per GWh of electricity produced (*ef*) has declined almost continually since 1950 (see Fig. 7) with a more rapid decline during the 1990s, since 2000 it has begun to creep up again, due to increased use of coal-fired power generators to meet the increasing electricity demand.

5.3 The 'Low Carbon' (LC) Scenario

The projected electricity consumption by fuel type under the LC scenario is shown in Fig 9. It can be seen that total demand is expected to reduce dramatically over time as a result of

energy conservation, technological innovation and product efficiency, environmental awareness, and changes to lifestyles and government policies. By 2050 the demand is reduced to about 200 TWh per year. Coal, conventional natural gas, and other thermal fuels are expected to be completely phased out in favour of CCGT/CCS. This will be the only remaining fossil fuel generating capacity in 2050 of about 30 TWh of electricity per year (Fig. 9). Nuclear power generation, due to a policy of “replacing nuclear by nuclear”, will be stabilise at around the same level as CCGT/CCS by 2050. Approximately half of the electricity demand, around 100 TWh, will be generated by onshore and offshore wind power with an increasing contribution from marine power schemes reaching almost 40 TWh per year by the end of the projection/scenario timescale. The remaining demand will be made up by small contributions from solar PV and small-scale (or natural flow) hydropower.

The LC scenario suggests (see Fig. 10) a more rapid decline in annual environmental footprint per GWh of electricity produced (*ef*) than under the BAU scenario; falling to 18 gha/GWh in 2050. However, the steepest decline occurs in the 2030s and 2040s, although this is still less steep than the decline seen in the 1990s. It would therefore appear to be attainable. In contrast to the BAU scenario, the LC scenario indicates an immediate decline of the total environmental footprint (EF), due to gradual replacement of coal and other thermal electricity generation by natural gas capacity with its smaller carbon total footprint (see Fig. 11). The decline in EF is sustained by demand reduction from about 2018, and by the gradual phasing out of convention gas power plant and its substitution by CCGT/CCS and wind power. Convention gas is consequently expected to account for less than 5 Mgha by 2050 under the LC scenario (Fig. 11). This scenario suggests that the proportion of the total environmental footprint resulting from carbon emissions will rise slightly before rapidly declining to a proportion of under 15% in line with the 2050 UK carbon reduction targets. The proportion from embodied energy will increase to about 70%, due to the construction of new build nuclear power and CCGT/CCS. Finally, the built land will increase to about 10% by 2050.

5.4 The ‘Deep Green’ (DG) Scenario

The DG scenario gave rise to a trajectory very similar to the LC scenario; see Fig 12. Total electricity demand is expected to dramatically fall over time again as a result of policies aimed at energy conservation, technological innovation and product efficiency, environmental awareness, and changes to lifestyles and government policies. By 2050 the demand is reduced to about 220 TWh per year. Since under the DG scenario the environmental imperative is considered as being paramount, coal, conventional gas, other thermal fuels, and nuclear will be completely phased out over the projection/scenario timeframe. CCGT/CCS will not be introduced, and by 2050 electricity generation will be dominated by renewable energy sources. Such renewables give rise to intermittency in electricity production, and extra provision has to be made in order to ensure energy security. Thus, the total demand is rather higher out to 2050 than under the LC scenario. The majority of the electricity demand under the DG scenario is envisaged to be increasingly met by wind power; that will reach some 170 TWh per year by 2050. Small-scale (or natural flow) hydropower will follow a similar pattern to that of the LC scenario, whilst marine power will provide a slightly smaller contribution and solar PV is likely to be higher in order to compensate.

The DG scenario projects a similar decline in annual environmental footprint per GWh of electricity produced (*ef*) to that of the LC scenario until the 2040s (see Fig 13), where more rapid decline results in a total footprint of just 6 gha/GWh in 2050. This fall is less steep than the decline observed in the 1990s, and was therefore regarded as attainable by Jardine and Ault [20]. In a similar manner to the LC scenario, the DG trajectory produces an immediate

decline of the environmental footprint, due to gradual replacement of coal and other thermal electricity generation by gas, which has a smaller total environmental footprint. Demand reduction from 2018 and gradual phasing out of conventional gas again sustain the decline in the total environmental footprint. However, CCGT/CCS is not adopted and nuclear power is completely phased out by 2025. Electricity demand is met by mainly wind power, and the total environmental footprint (EF) is projected to be only 1.2 Mgha in 2050 (see Fig 14). Initially the proportion of this footprint resulting from carbon emissions (footprint or weight) according to the DG scenario is similar to the LC scenario, although after 2040 it declines more rapidly in order to reach zero in 2050. The embodied energy proportion also declines, due to the phasing out of large centralised generators (such as conventional thermal and nuclear power stations), which require large amounts of infrastructure and involve energy intensive construction processes. Nevertheless, the built land proportion of EF increases somewhat, due to the physical area required for new wind farms.

6. CONCLUDING REMARKS

Electricity generation contributes a large proportion of the total greenhouse gas emissions in the UK, due to the predominant use of fossil fuel (coal and natural gas) combustion for this purpose. Carbon and environmental footprint analysis has therefore been employed to estimate the environmental impacts associated with UK power generation based on historic data and alternative energy scenarios out to 2050. The British Government has set a legally binding target of reducing the nation's CO₂ emissions by 80% over this timescale in comparison to a 1990 baseline. It is recognised that in order to achieve this target, the UK *Electricity Supply Industry* (ESI) needs to be decarbonised over this period. In order to determine future trends in the power sector footprints, a range of future energy scenarios were adopted that had previously been developed for the UK SUPERGEN Consortium on '*Highly Distributed Power Systems*' (HDPS) by Jardine and Ault [20]. They were developed from a synthesis of those that had been earlier devised for future network technologies on the one hand, and domestic energy demands on the other. Three resulting scenarios were characterised as 'Business As Usual' (BAU), 'Low Carbon' (LC) and 'Deep Green' (DG) futures, and yielded possible future electricity demands to 2050. The BAU scenario is based on incremental change over time with a continuation of near-term trends in technologies (see Fig. 6), and energy policy responses to the climate change and energy security challenges. Growth in the take-up of decentralised energy resources (DERs) is assumed to be consumer-led, rather than stimulated by an act of government policy intervention. In contrast, the LC scenario implies an extensive penetration of micro-generators in the home to satisfy heat and power demands (the former not displayed in the present work). However, these energy requirements are minimised by way of improved insulation of the building fabric and other demand reduction measures. Under this scenario, DERs contributes ~44% of UK electricity supply by 2050 (not shown in Fig. 9, which only shows the electricity produced by ESI network power generators), and residential dwellings are significant net exporter of power. Finally, the DG scenario presupposes a network where centralised renewable energy technologies – mainly large-scale onshore and offshore wind turbines - have an important role in the power generation (see Fig. 12). Demand reduction again plays an important role (in a similar manner to that with the LC scenario), but fossil fuel power generation is effectively eliminated.

Methodologies were established for the present study to calculate the environmental and carbon footprints of the UK electricity industry on both a historic timescale and in accordance with the HDPS scenarios. These were consistent with that developed by the *Global Footprint*

Network and related bodies. The environmental footprint was broken down respectively into carbon (effectively *cf*), embodied energy, transport, built land, water, and waste components. Annual environmental footprint per GWh of electricity produced (*ef*) was then calculated over the timeframe of 1950-2050. Uncertainties related to both footprints were estimated using an established procedure for uncertainty analysis. It was found that the current total environmental footprint (EF) as a result of UK electricity supply and demand is 41 Mgha, with an estimated uncertainty of $\pm 4\%$. If future trends follow the HDPS BAU scenario this footprint in 2050 is projected to fall to about 25 Mgha ($\pm 3\%$), whereas both the LC and DG scenarios lead to footprints of less than 4 Mgha ($\pm 5\%$). The latter two scenarios were found to give rise to quite similar trajectories out to 2050. It is argued that the latter two scenarios are more likely to reflect an effective transition pathway in terms of meeting the 2050 CO₂ reduction targets for electricity generation, with the ‘Deep Green’ scenario proving the preferred choice if complete decarbonisation of UK power generation were deemed desirable.

The UK Government established an independent *Committee on Climate Change* (CCC) in the *Climate Change Act 2008* in order to advise it on progress towards meeting its overall carbon reduction target of 80% by 2050 from heating, power and transport fuels against the 1990 baseline. This adopted a new approach to managing and responding to climate change in the UK, and led to the creation of a legally binding target for reducing Britain’s GHG emissions. A 37% emissions reduction by 2020 (relative to 1990) was proposed under the tightening of second and third CCC carbon budgets [29]. Required reduction in emissions from 2010 until 2030 was set as 46%. The CCC also advocated deep cuts in power sector emissions through the 2020s [29], with UK electricity generation becoming largely decarbonised by 2030-2040. The present HDPS scenarios (see, for example, Fig. 8, 11 and 14 [20]) suggest that there might actually be a fall in carbon emissions from the UK power generation sector [using the total environmental footprint (EF) here as a proxy for overall carbon emissions] of some 9-19% by 2020, 16-55% by 2030, and 26-97% in 2050. The lower figures relate to the BAU scenario, whilst the higher ones are associated with the other two futures. Thus, the present HDPS scenario (see again Fig. 8, 11 and 14) projections indicate that the UK ESI could only be decarbonised by 2050 under the LC and DG scenarios. This is because the present EF estimates take account of upstream emissions (i.e., those associated with the ‘embodied energy’ component), whereas the projections by bodies like the CCC and UK Government’s *Department of Energy and Climate Change* (DECC) only make allowance for direct or operational GHG emissions from power plant combustion.

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APPENDIX: Uncertainty Analysis of Environmental Footprints

The uncertainties in the footprints of each component were calculated using a 'standard' method developed originally by Kline and McClintock [19] for single-sample experiments in engineering research. A more accessible description of the technique is given by Holman [30]. Here estimates of uncertainties were based on a careful assessment of errors in the various primary and secondary (or proxy) sources (see also Eaton *et al.* [15]). The result of an experiment or study can be expressed using a function of the variables:

$$R = R(x_1, x_2, x_3, \dots, x_n)$$

If W_r is the uncertainty in the final result (the footprints), and $W_1, W_2, W_3, \dots, W_n$ are the uncertainties in the individual variables, then the uncertainty in the result is given by [19,30]:

$$W_r = \left[\left(\frac{\partial R}{\partial x_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} W_n \right)^2 \right]^{1/2}$$

In the present footprint study, the primary data consisted of resource consumption estimates used to determine each component of the footprint. The function employed to calculate the overall footprint (EF) of the HDPS scenario projections can be expressed in terms of the different components, viz:

$$\text{Total Environmental Footprint} = \text{Carbon Footprint} + \text{Embodied Energy Footprint} + \\ \text{Transport Footprint} + \text{Built Land Footprint} + \text{Water Footprint} + \text{Waste Footprint}$$

To simplify the calculations, the uncertainty for each component was initially estimated by considering them separately. These uncertainties were then used to determine to total

uncertainty in the footprint. In addition, these uncertainties were converted into percentage values for each component. The total uncertainty was obtained by summing the uncertainties for each component. Here the calculated uncertainty in the total environmental footprint (EF) is shown in Table 1 below. The uncertainties associated with each of the individual component are also displayed there. It can be seen that those for the built land, carbon and water components are all in the range ± 4.0 -5.3%, whereas those for embodied energy, transport and waste were roughly double that. Nevertheless, the weightings resulted in an overall uncertainty of $\pm 4.35\%$ for the environmental footprint of the UK power network in the base year.

**Table 1 – Total Environmental Footprint (EF) of the UK Power Network:
Uncertainty for the Base Year [*circa* 2005]**

	Footprint (thousand gha)	Uncertainty	$\left(\frac{\partial R}{\partial x} w\right)^2$
Carbon	20554.3	4.84%	971466
Embodied energy	17455.6	8.46%	2182991
Transport	705.9	9.01%	4043
Built land	1192.7	5.22%	3870
Water	77.8	4.07%	10
Waste	964.7	10.65%	10566
Total	40951.1		3172945
Uncertainty-factor (gha)			1781.3
Uncertainty			4.35%

NB: The data sources employed here would suggest that these estimates are only valid up to an accuracy of not more than three significant figures.

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Energy Transformation System



























